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Cincinnati, Ohio

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LIGHT-SCATTER INSTRUMENTATION FOR MEASUREMENT OF ATMOSPHERIC PARTICULATES

J. S. Nader, G. C. Ortman, and M. T. Massey

Atmospheric particulates consist of solid particles and liquid droplets ranging in size from millimicrons to tens of microns and varying in shape from spherical fog droplets to porous and irregular soot particles. Their source could be natural, the result of condensation, dust storms, and forest fires or artificial, resulting from the labors of man and industry. Particulates are considered pollutants inasmuch as they can reduce visibility, cause property damage, and produce toxic effects both in man and plant life. As man-made pollutants, they are subject to abatement and control. Instrumentation is necessary, therefore, to evaluate the contribution of man-made particulates to the air pollution problem, the nature of various particles and their correlation to specific effects, and the effectiveness of specific control measures.

Instrumentation for the detection and measurement of particulate can operate according to any one of a number of principles which relate to the nature of the particle. For example, the mass of a particle will allow for inertial collection and analysis; the charging property for its electrostatic detection; its radioactivity for its nuclear measurement; and its optical properties for light-scatter measurements.

Collection and analysis of such small particles have been known to present some difficulties. Low particulate concentrations require long sampling periods to collect a sample which could be weighed to give mass concentration. Such concentrations, then, only represent an average value for a long time interval but give no measure of short term variations. The

sampling method takes into consideration filtering efficiency, air flowrate, and sampling medium which must meet the requirements of the subsequent method of analysis. Some of the analytical methods of microscopy, gravimetry, or photometry may emphasize aspects of sampling that are contradictory. A gravimetric sample needs to be large for accurate weighing. A sample for microscopic analysis, on the other hand, has to be fairly light to distinguish individual particles for particle sizing or chemical spot tests. Furthermore, the need for collection of a sample prior to analysis provokes a question which will most often be asked, namely, how much of an agglomerating effect is there in any given sampling technique? Or more simply, how representative is the collected sample of its prior existence in the sampled air?

Photoelectric measurement of light scattered by particulate offers a sensitive method of analysis without some of the drawbacks of sample collection. The method is sensitive in the particle size range of immediate interest, from 0.2 to 2 μ diameters. Particles in this size range are, to a great extent, retained in the lungs and can be a potential health hazard. Furthermore, since particles in this size range have diameters near the wavelength of visible light, they have optimum visible light-scatter characteristics and the undesirable effect of reducing visibility.

MASS AND PARTICULATE CONCENTRATION

Early photoelectric devices were developed to measure relative particle concentrations in the evaluation of smoke respirators and filtering media.[1] A sensitive method by Gucker, et al[2] consisted of a measure of light scattered by the particulate in an air stream at right angles to the path of the incident light beam. This method was satisfactory as long as the size

distribution remained constant and the objective was a measure of the relative concentration of two samples of particulates of the same size. It had the disadvantage that measurements were affected by any change of light intensity between the calibration with a test aerosol and the measurement with the sampled aerosol. In addition, measurement of absolute instead of relative concentrations required standardization with a known aerosol concentration.

Subsequently, Peterson[3] developed a differential photometer which used the optical system developed by LaMer and Sinclair.[4] Dark-field illumination was used to illuminate the sampled particles which scattered light in the near-forward direction (between 5 and 35° from forward) onto a photomultiplier. The photomultiplier permitted increased sensitivity and stability over the vacuum photocell and associated electronics of the simple right angle scatter instrument. This improved photometer also compensated for any change in light intensity or photomultiplier sensitivity by using a portion of the incident light beam as a reference beam which is periodically monitored by the photomultiplier through a rotating shutter. Any deviation of the photomultiplier output from a preset level, due to changes in light intensity or phototube gain, was amplified and activated a motor which varied dynode voltage on the photomultiplier and thus brought about a change in sensitivity and the necessary compensation.

A right angle light-scatter photometer was later developed by Mendenhall[5] who used essentially the same concept of splitting the incident light beam to give a reference monitor beam which automatically compensated for changes in incident light intensity or photomultiplier gain. The dynode voltage in this case was varied by negative electronic feedback instead of electromechanically by a servomotor drive.

The performance of the "Monitron"* (Fig. 1), a commercial version of Mendenhall's development, is currently being evaluated as a continuous monitoring device and in conjunction with other related measurements of mass particulate concentration in the atmosphere. The optical system (Fig. 2) and the electronic system (Fig. 3) follow essentially the prototype version. The light from a 6-volt automobile headlight bulb is split into two beams, the monitor beam, I_m, and the incident beam, I_i. Both beams are alternately interrupted by an arrangement of holes in the rotating light chopper disc. The monitor beam is reflected into the photomultiplier by several 45° mirrors, one of which has an adjustable angle of reflection so that the intensity of the monitor beam reaching the photomultiplier can be increased or decreased. The point of right angle intersection of the incident beam and the path of view of the photomultiplier is the "optical volume" which is in an isolated compartment of the instrument, through which sampled air is pumped by a squirrel cage blower having an air flowrate of approximately 6 cfm. The air flowrate can be decreased by reducing the size of the exhaust outlet. Particles present in the optical volume will scatter light, I_s, from the incident beam onto the photomultiplier. Consequently, the photomultiplier will have a pulsed output signal for the monitor beam 180° out of phase with the pulsed output signal for the scattered light beam. The two signals are separated by the commutator which is attached to the shaft of the light chopper. The pulsed signals are integrated by a small time constant (approx. 0.5 sec.) circuit which provides a D.C. signal to the meter. By feedback of the monitor output signal, the overall gain of the instrument, i.e., photomultiplier

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*Engineering Specialties, 8115 Camargo Road, Madeira, Ohio

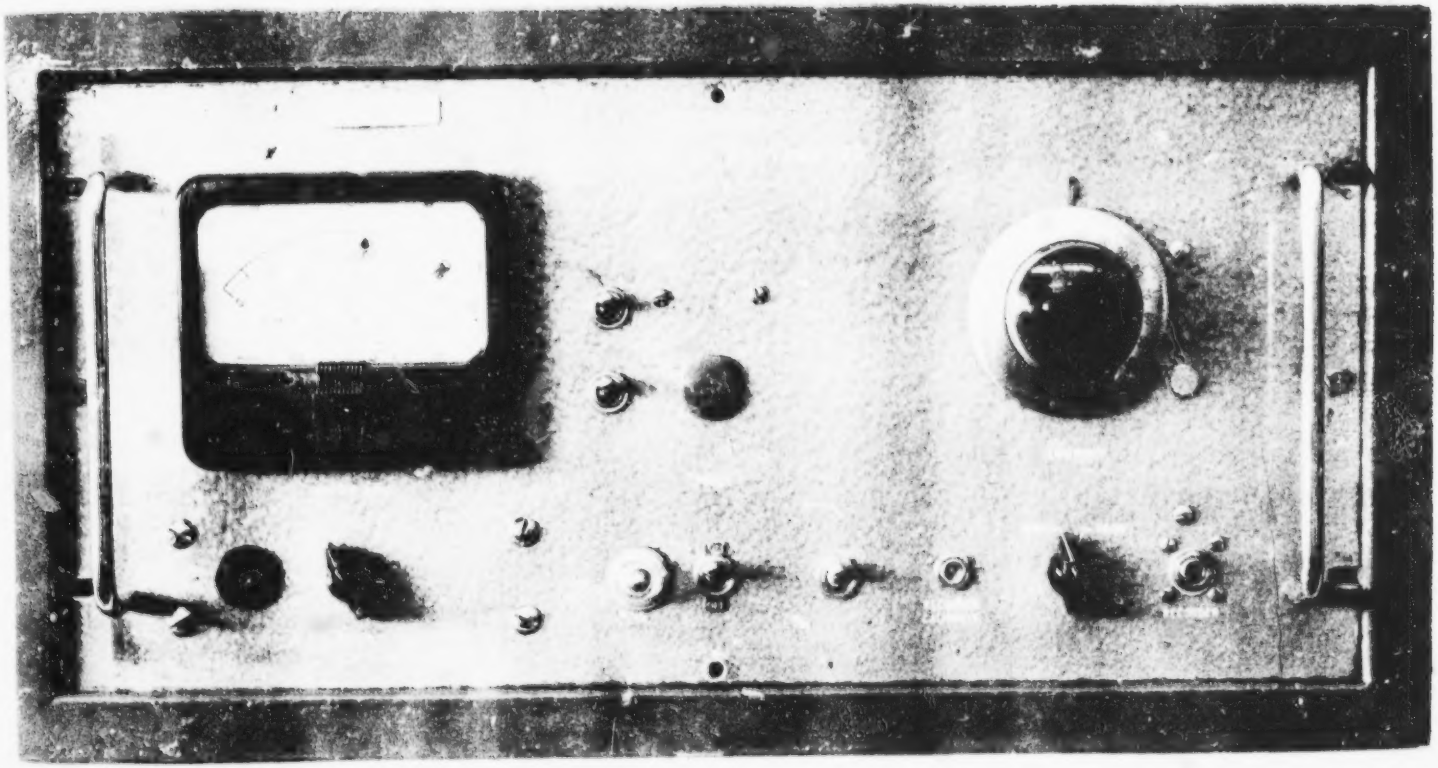

FIGURE 1

OPTICAL SYSTEM

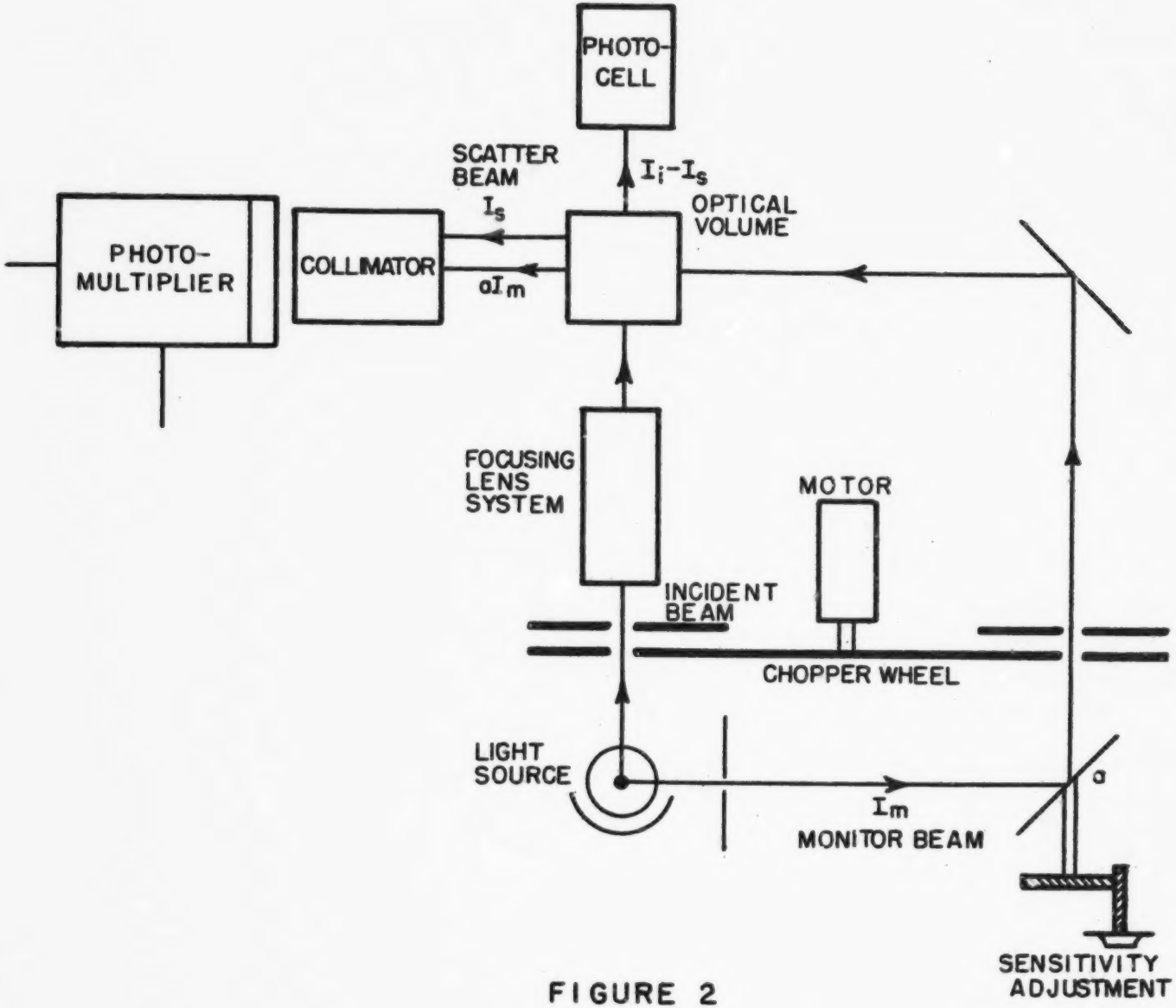

FIGURE 2

ELECTRONIC SYSTEM

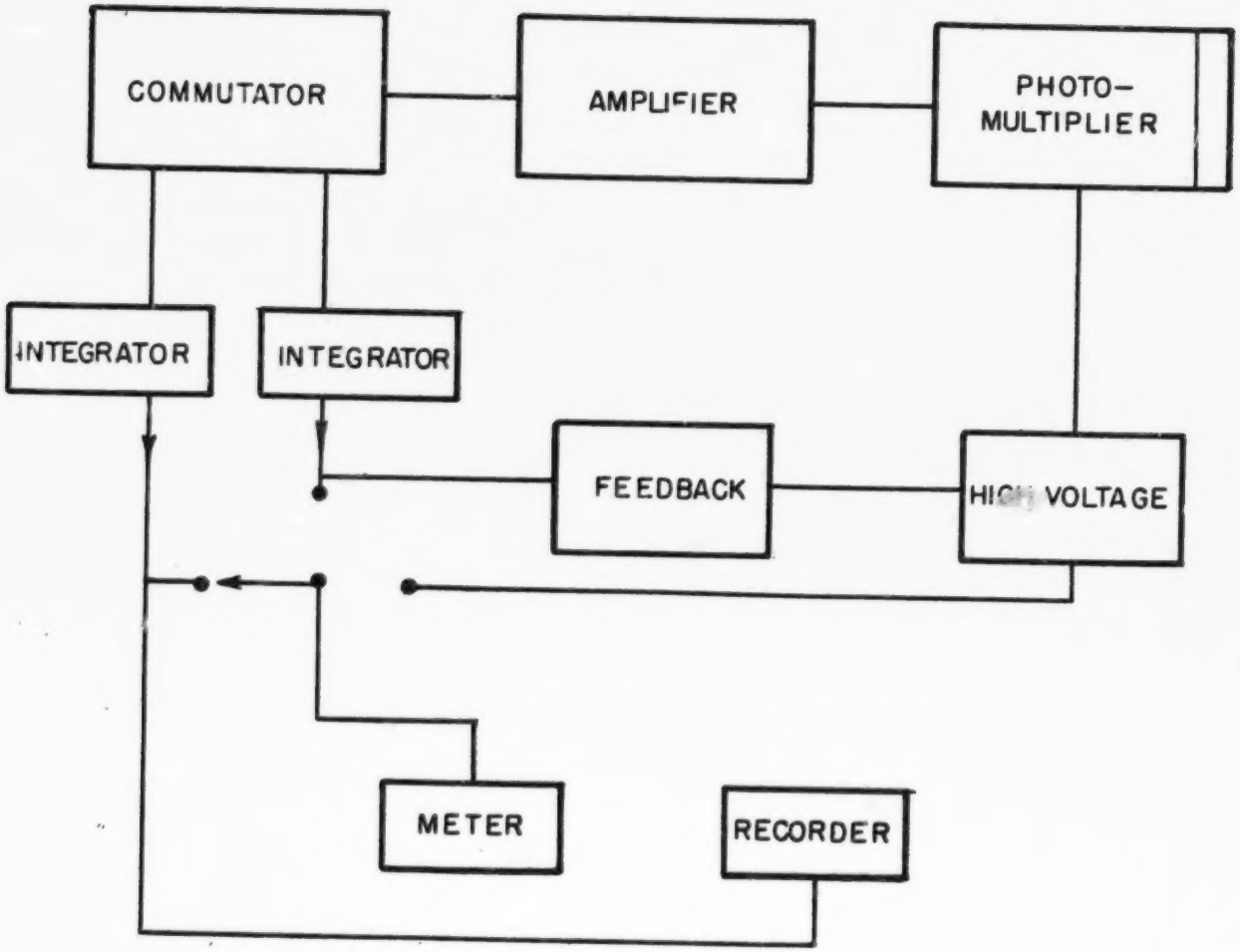

FIGURE 3

sensitivity and light source intensity, is automatically adjusted to maintain a constant monitor signal output, R_m, against which the scatter light signal is referenced.

A better understanding of the interpretation of the meter reading, R_s, for the scattered light, in terms of the light-scatter coefficient, σ, can be shown briefly as follows:

$$R_S = GSI_S = GAc\sigma I_o \quad (1)$$

$$R_m = GAaI_m = GAabI_o \quad (2)$$

where R_m = Meter reading of monitor beam, a constant

R_s = Meter reading of scattered light beam

A = Amplification factor of amplifier and a constant

a = Coefficient as function of sensitivity setting

I_o = Light source intensity

I_s = Scattered light beam

I_m = Monitor light beam

$b = \frac{I_m}{I_o}$

I_i = Incident light beam

$c = \frac{I_i}{I_o}$

σ = Light-scatter coefficient, $\frac{I_s}{I_i}$

G = Gain of photomultiplier, which, because of negative feedback, is an inverse function of I_m or bI_o.

$$R_S = \frac{R_m}{ab}\sigma = K\sigma \text{ where } K = \frac{R_m}{ab} \quad (3)$$

The results in Eqn. (3) show that R_s is directly proportional to the scattering coefficient. Furthermore, for a given scattering coefficient, R_s is a function of the sensitivity setting or an inverse function of the intensity of the monitor beam as seen by the photomultiplier.

Minor modifications were made on the Monitron in our laboratory as the need arose. These consisted of the addition of a reflector on the light source to increase the scatter signal (by a factor of 4); addition of a photovoltaic cell at the end of the incident light beam to observe relative changes in source intensity; the installation of a manually operated shutter to block the incident light beam for a measure of the dark current response of the photomultiplier; and the installation of a light-scatter probe which can be manually introduced into the optical volume as a test reference for the overall response of the optical and electronic system.

PARTICLE COUNT AND SIZE DISTRIBUTION

Most of the important effects of atmospheric particulate in the study of air pollution, such as reduced visibility, soiling, corrosion, control, etc., are strongly dependent upon the particle size and number. Hence, measurement of these particle parameters is of importance.

Again, the history of the development of the particle counter shows that a counter based on light-scattering was developed, Gucker, et al,[6] to provide an ultra-sensitive test of gas mask service cannisters by determining the penetration of single aerosol particles slightly larger than 0.3 μ diameter used in penetrometer tests. This was followed by a second counter developed for counting and measurement of particle size by pulse discrimination.[7] Subsequent developments became more complex with the use of

multiple channel analyzers and associated readout accessories. The size alone of the composite instrument for particle count and size analysis limited its use to a fixed installation with controlled aerosols. A study of the particle parameters of atmospheric particulate, however, required a field type instrument which would be portable with a self-contained power supply. To meet this need, the U. S. Public Health Service contracted for and has received delivery of a miniaturized light-scatter photometer and pulse-height analyzer for field measurements of particle count and size distribution.* The instrument has been designed to make these measurements of aerosols in the atmosphere and of solid particles or liquid droplets in gases.(8) The instrument is portable and battery operated, employing transistor circuitry (Fig. 4). The counter measures 14 1/2" x 5" x 8 7/8" and weighs 10 1/2 lbs.

The operation of the instrument is as follows: Air is drawn through the flow system (Fig. 5) at a rate of 17 cc/min. by a small positive displacement gear pump. Dilution air is obtained from the environment through a high efficiency filter. The dilution valve gives the desired ratio of dilution to sample air. This can be set from zero dilution (totally sampled air) to infinite dilution (totally filtered air) and calibrated at intermediate dilution factors of 5, 10, and 20. Filtered air surrounds the sample air stream to prevent dispersion of particles in the photometer head and to maintain laminar flow of the sample stream through the optical volume. For concentrations within full scale range, particles are viewed one at a

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*Developed under Contract No. SAph 78964 for the Robert A. Taft Sanitary Engineering Center, U. S. Public Health Service.

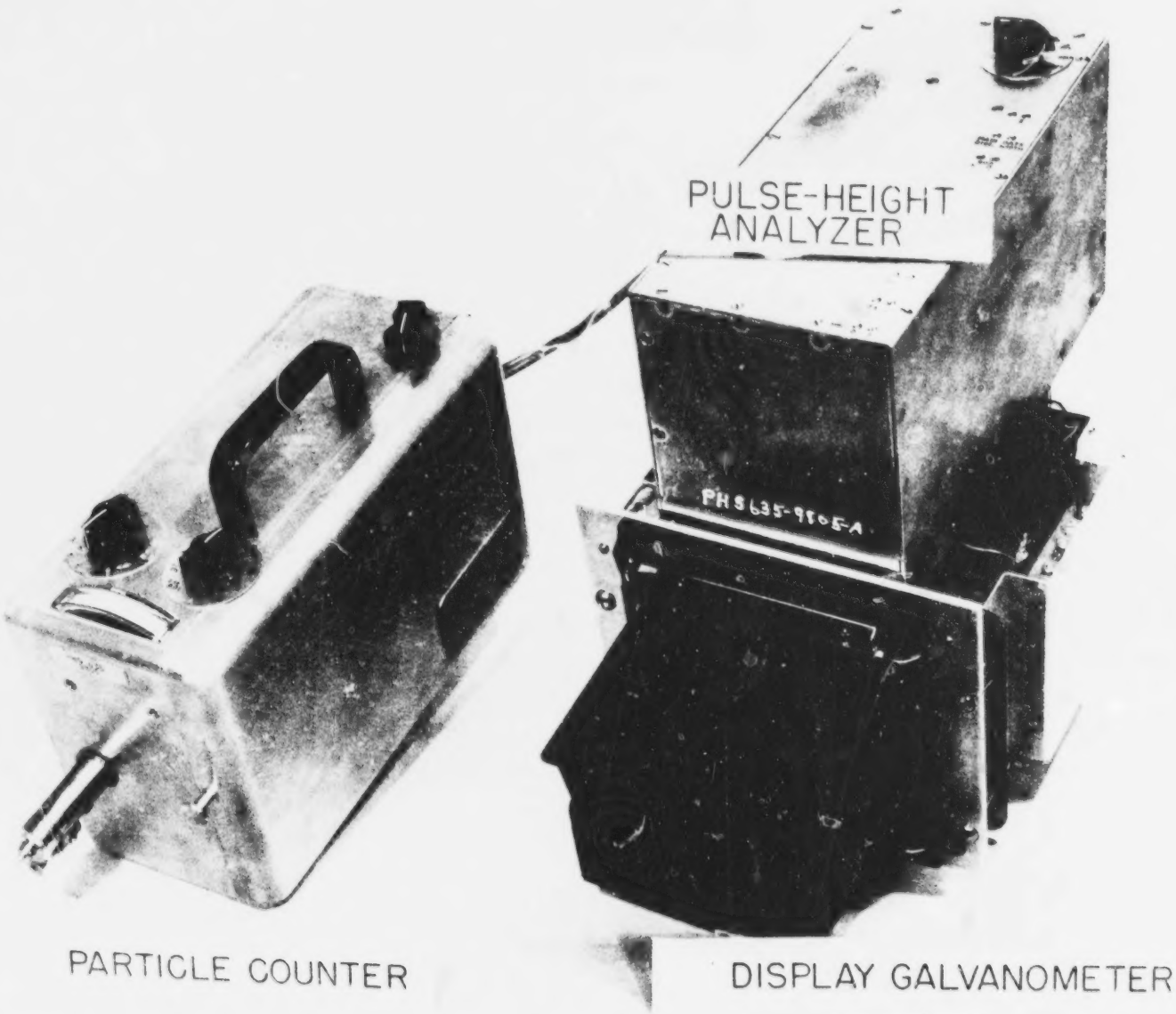
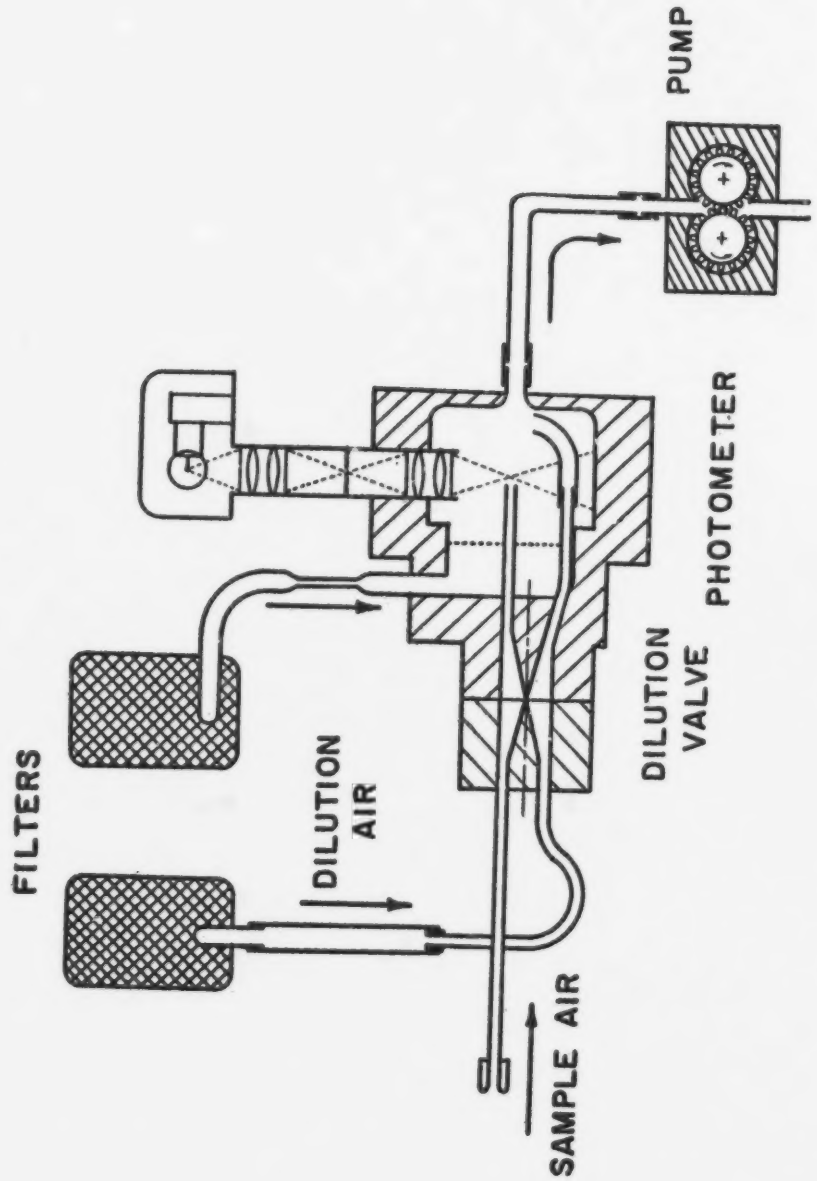

PULSE-HEIGHT
ANALYZER
PHS 635-9505-A
PARTICLE COUNTER
DISPLAY GALVANOMETER

FIGURE 4

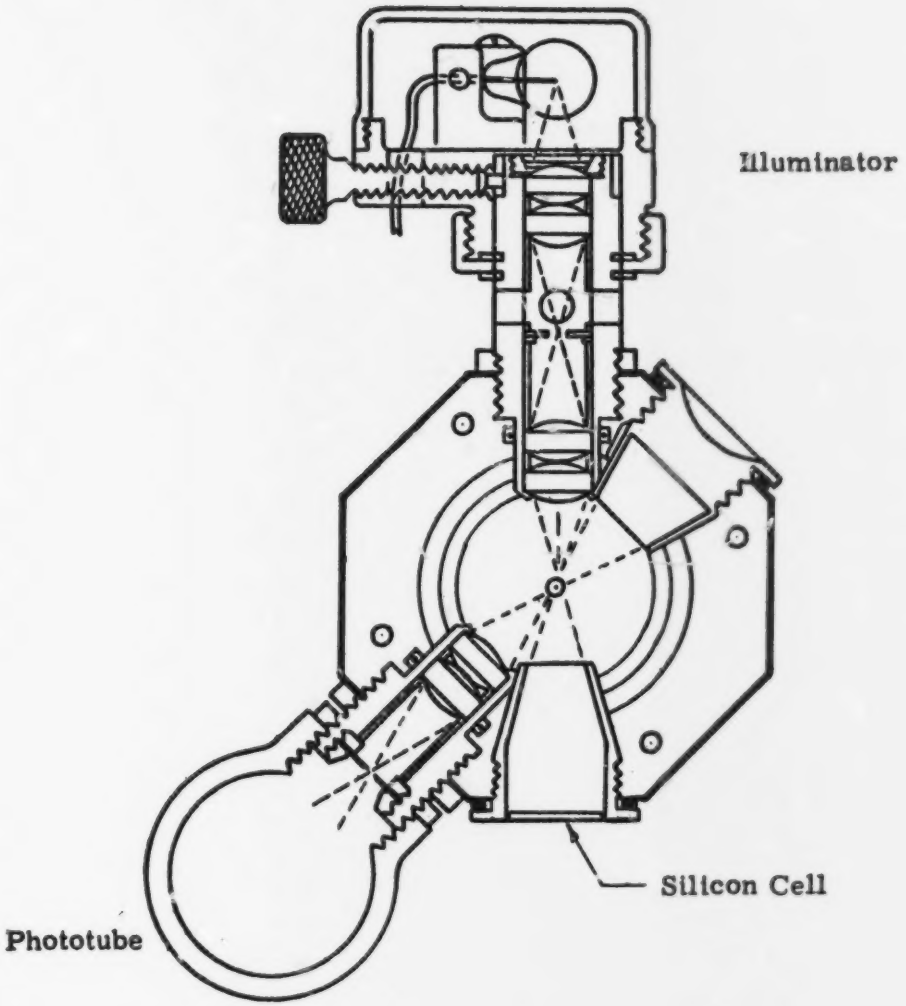


FLOW SYSTEM
FIGURE 5

time as they are drawn into the illuminated optical volume of 0.5 microliters (Fig. 6). The scattering angle is 135° from the incident light beam.

The photomultiplier tube produces an electrical pulse of approximately 1 millisecond duration from the light scattered by each particle. These pulse amplitudes are analyzed for electrical size distribution and displayed in terms of particle size diameters, based on calibration with monodisperse polystyrene spheres. Pulses produced at the phototube are amplified and applied to the one discriminator of the particle counter and to each channel discriminator of the particle size analyzer (Figs. 7 & 8). The discriminator output pulses are then amplified and counted. An electrical signal proportional to the logarithm of the number of pulses is indicated on the meter of the particle counter; similarily, a channel signal is used to drive each galvanometer of the pulse-height analyzer.

For manual size analysis the particle counter may be operated independently to obtain a count of particles above a given size. The cut-off is adjustable from 0.3 to 2 microns by a manually operated discriminator. A series of readings at various cut-off sizes will give a cumulative distribution of particle count vs. size. Automatic size analysis in the range from 0.3 to 10 microns is obtainable by operation of the particle counter in conjunction with the 12 channel pulse-height analyzer. A size distribution histogram of the analyzer output is displayed on the screen of a multi-channel galvanometer. There are also simultaneously displayed the values for the dilution factor and the total particle concentration. The entire display may be "frozen" at any instant to permit photographing the information (Fig. 9).



FUNCTIONAL DRAWING OF THE PHOTOMETER

FIGURE 6

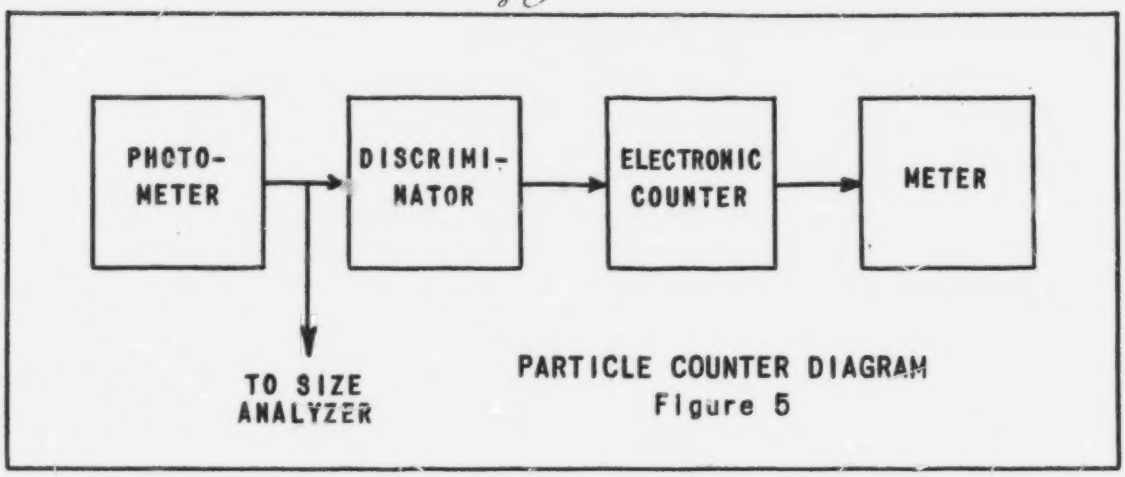


FIGURE 7

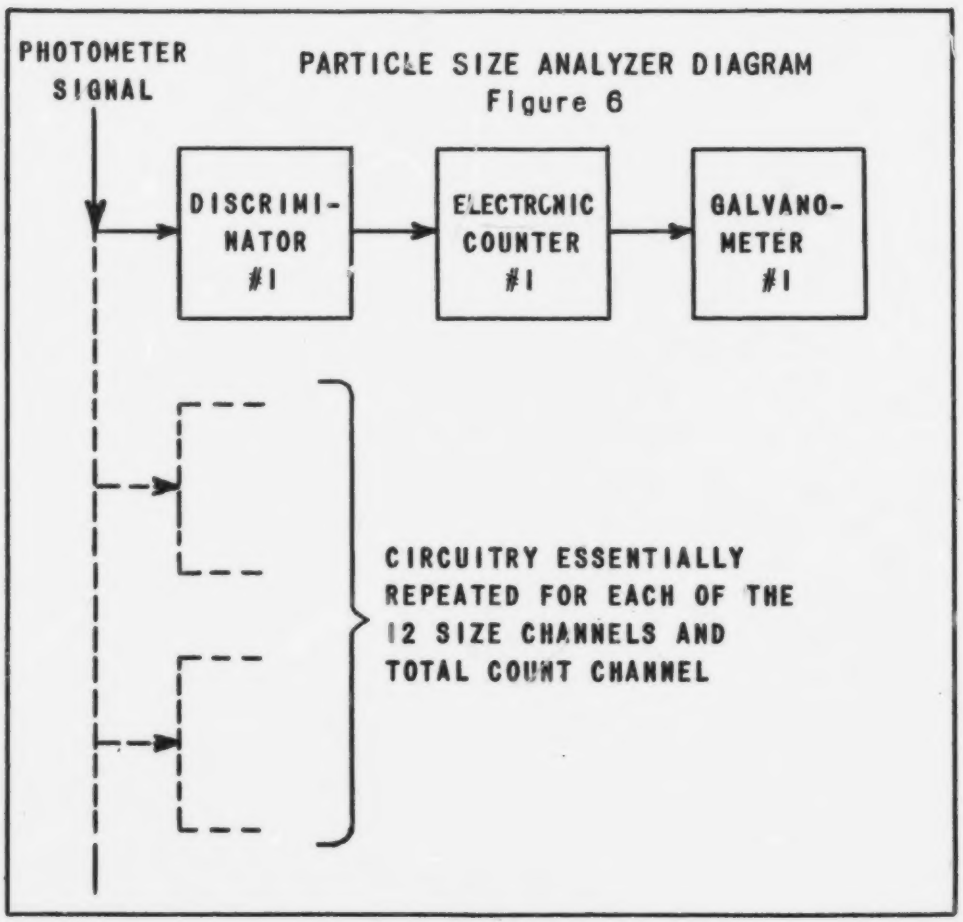


FIGURE 8

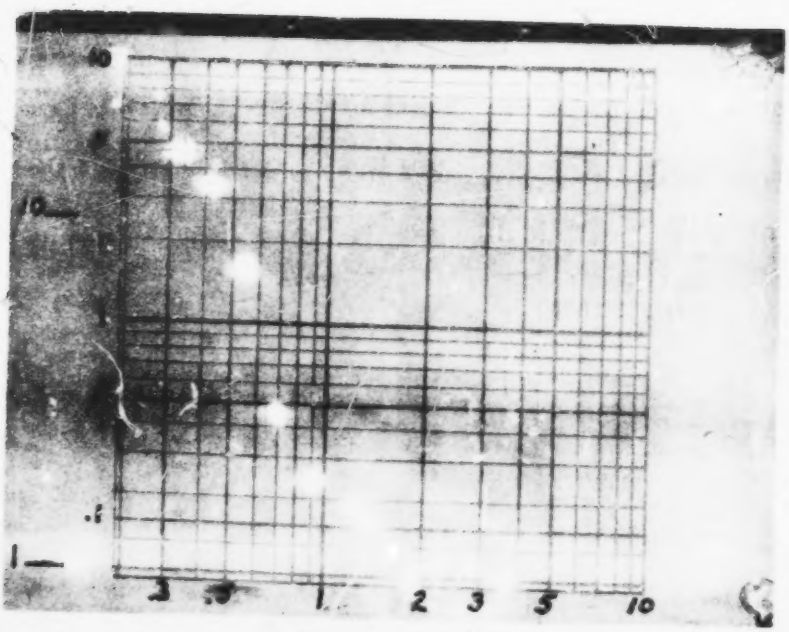


FIGURE 9

Particles may be counted at a rate of 10 and 100 per second corresponding to an undiluted concentration of 1 and 10 million particles per cubic foot, respectively. For a dilution factor setting of 10 these correspond to 10 and 100 million particles per cubic foot, respectively. Particle count may also be accumulated over a period of time for concentrations less than 1 million particles per cubic foot. Maximum reading time is 2 minutes which gives a full scale value of 0.5 million particles per cubic foot. With the log scale this gives a minimum readable concentration of 5 thousand particles per cubic foot.

FIELD MEASUREMENTS AND DISCUSSION

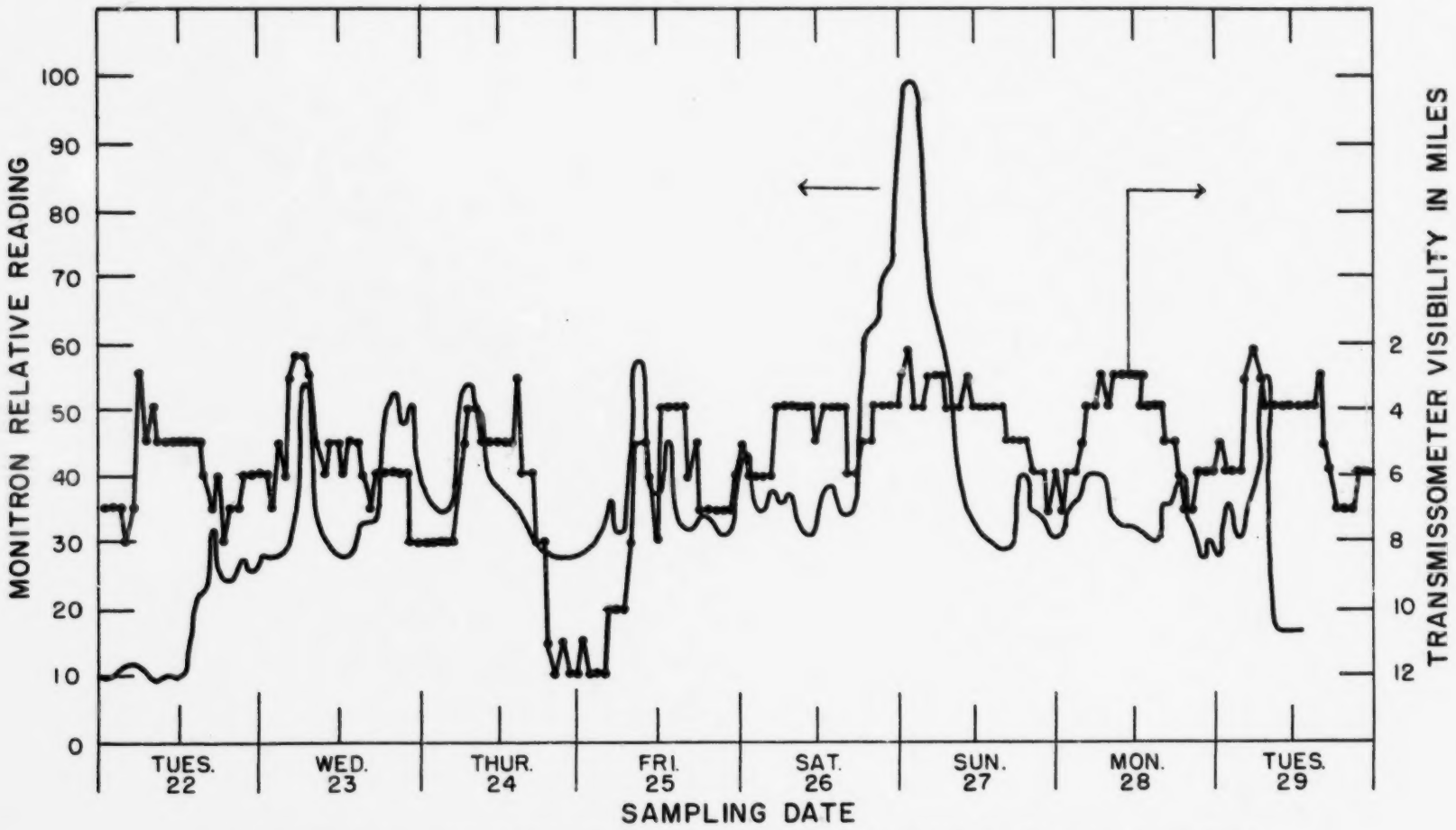
As part of a preliminary study initiated to observe what correlation may exist between various air quality measurements of particulates, a number of particulate measuring instruments were operated for the greater part of March at the Gest Street Experimental Facility of Air Pollution Engineering Research, Robert A. Taft Sanitary Engineering Center. The Gest Street Facility is located in an industrial environment close by the downtown area of Cincinnati and is instrumented to measure meteorological parameters and to obtain various air quality data. Operating concurrently at various times with the Monitron were the following instruments: transmissometer which measured the attenuation of light by atmospheric particulate over a 750 foot path length and whose data is expressed in miles of visibility; membrane tape samplers for subsequent soiling and mass loading analysis of particulate; portable particle counter and size analyzer.

Particulate collected on membrane tape[9] for 4 hour intervals was analyzed using the mass loading analyzer[10] to express the data in terms

of average mass concentration per unit volume for the specified time interval, i.e., micrograms per cubic meter. The analyzer used a beta gauge technique to measure the thickness of particulate deposition and was operating near its limit of sensitivity to detect the small thicknesses of particulate (≤ 0.1 mg/cm^2) collected in the 4 hour interval. Particulate also collected on membrane tape for 2 hour intervals was analyzed by light transmission measurement of the particulate depositions.(11)

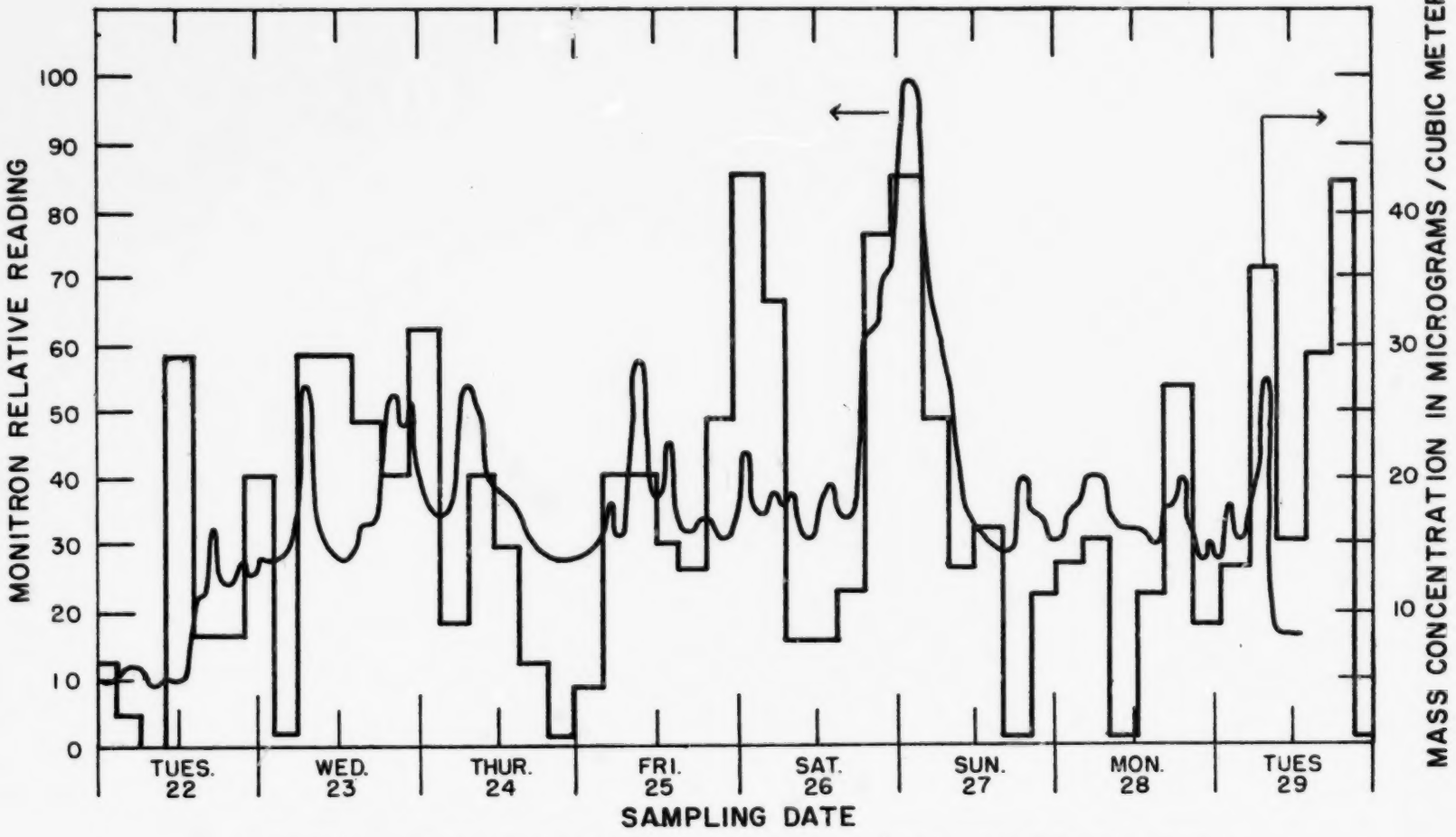
Data obtained over a period of one week in March during which all the instruments were operative were graphically evaluated for comparisons of various air quality measurements. The curves of one hour average values for the Monitron's light-scatter readings and the transmissometer's visibility readings show some graphical correlation in the rise and fall of both values (Fig. 10). This is what one might expect considering that both instruments operate on light-scatter principles. It is well known, however, that light-scatter from natural pollutants such as fog plays a significant role in transmissometer measurements. Additional study of the data will be necessary to observe what effect high humidity has on the Monitron measurements and the possibility of reducing this effect by some technique such as preheating the sampled air. Further evaluation of the data may indicate that the correlation is sufficiently high to permit calibration of the Monitron in terms of visibility readings. Such an approach will provide a practical and convenient means of instrumenting visibility measurements.

The correlation which appears between mass concentration and light-scatter values (Fig. 11), would also indicate the possibility of empirical calibration of the Monitron for measurement of mass concentration of atmospheric particulate, thus eliminating the need for sample collection and providing a



COMPARISON OF MONITRON AND TRANSMISSOMETER DATA

FIGURE 10



COMPARISON OF MONITRON AND MASS LOADING DATA

FIGURE 11

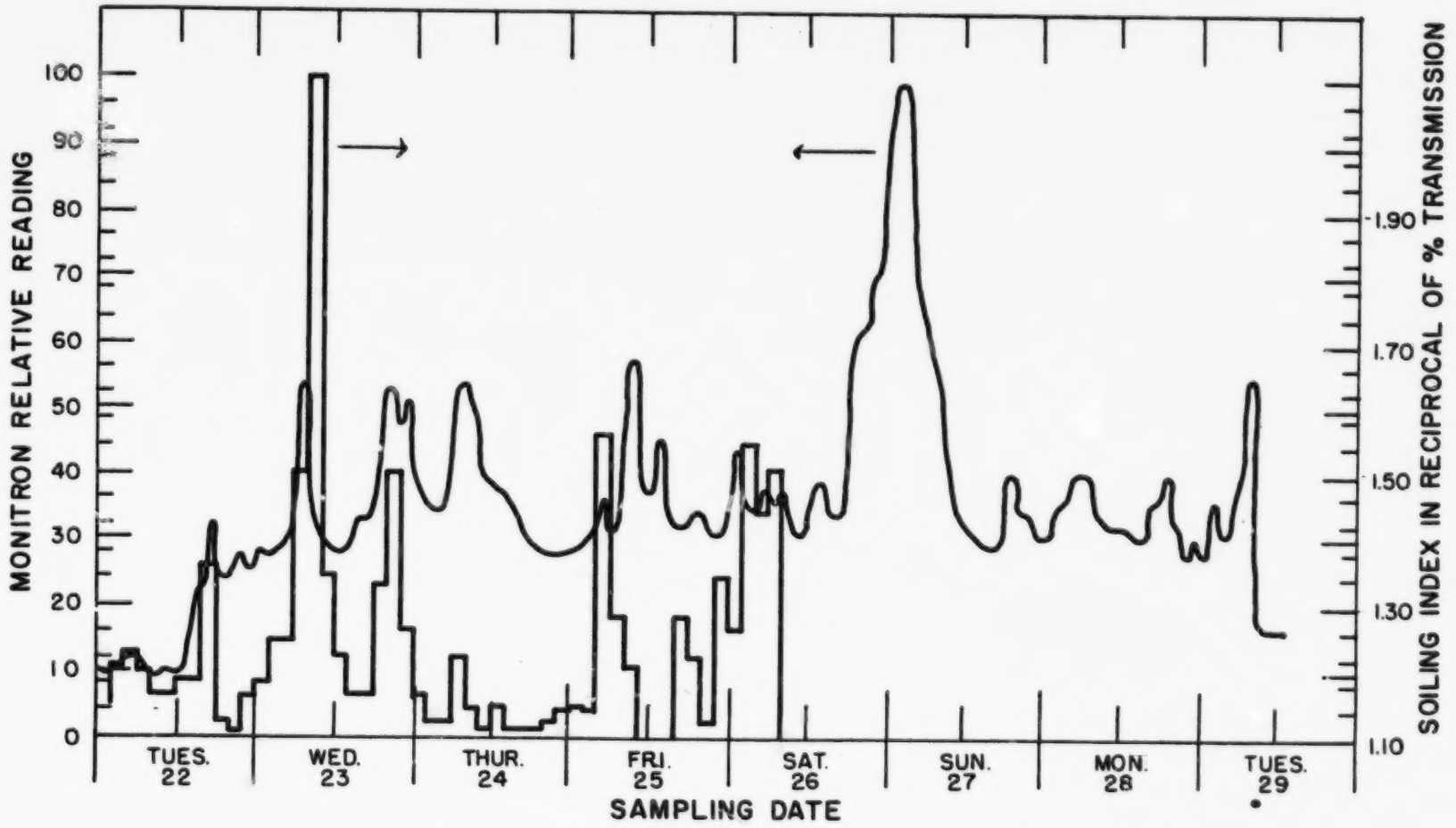
sensitive measure within a shorter time interval. Additional work will be necessary, however, in which monodisperse polystyrene spheres of known sizes, as well as representative atmospheric particulate samples, are used to obtain information on the effect of various particle diameters and size distribution and particle number on mass loading calibration.

Data on the soiling index was limited to part of the period of interest due to malfunction of the sampler later in the week (Fig. 12). There are indications of some correlation which will have to be looked into further.

The particle size analyzer was operated on several occasions during this period and the size distributions which were obtained did not show anything significantly different from the distribution shown in Fig. 9. The log scale on this curve indicates a predominance in the number of particles below 2 microns and a peak in the distribution somewhere below 0.3 microns. Considering that the atmospheric content of particulate is a composite of particles from different sources more or less in equilibrium, it is very likely that this distribution will be representative until a specific source of high output has a drastic change in its contribution.

The light source of the particle counter had a relatively short life of about seventeen hours and maintained a fairly constant intensity without adjustment for about 2-4 hours. As a result it did not lend itself to continuous unattended monitoring over any length of time. Data was obtained, however, concurrently with the other air quality measurements to permit a calibration in terms of particle count.

All the graphical data shown is being statistically evaluated to obtain correlation values which should provide a reliable quantitative measure of the graphical interpretation. Additional field data will be required to substantiate these preliminary findings on the use of light-scatter values



COMPARISON OF MONITRON AND SOILING INDEX DATA

FIGURE 12

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as a measure of visibility, mass loading, and scaling parameters of atmospheric particulate.

ACKNOWLEDGEMENT

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